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Understanding microwave induced sorting of porphyry copper ores

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ABSTRACT

Global demand for minerals and metals is increasing. It has been established that the impact of mining and mineral processing operations must be reduced to sustainably meet the demands of a low grade future. Successful incorporation of ore sorting in flow sheets has the potential to improve energy efficiency by rejecting non-economic material before grinding. Microwave heating combined with infrared temperature measurement has been shown to distinguish low and high grade ore fragments from each other. In this work, experimentally validated 2-D finite difference models of a theoretical two phase ore, representing typical fragment textures and grades, are constructed. Microwave heating is applied at economically viable energy inputs and the resultant surface thermal profiles analysed up to 2 min after microwave heating. It is shown that the size and location of grains can dramatically alter surface temperature rise at short thermal measurement delay times and that the range of temperatures increases with increasing fragment grade. For the first time, it is suggested that increasing the delay time between microwave heating and thermal measurement can reduce the variation seen for fragments of the same grade but different textures, improving overall differentiation between high and low grade fragments.

1. Introduction

The mineral processing industry's current ability to meet the demands of a low grade future has prompted discussion about a required step change (Bearman, 2013). Current flow sheets are highly energy intensive; estimates suggest that comminution alone accounts for around 2% of worldwide electricity demand (Napier-Munn, 2014). With global concerns surrounding climate change, the mining industry is under pressure to improve environmental sustainability by reducing energy, greenhouse gas and water footprints (Pearce et al., 2011), whilst meeting increasing demands for minerals and metals (Fu, 2012), as ore grades are falling (USGS, 2012).

For both existing and new mineral processing operations, early rejection of gangue via sorting (at fragment sizes typically found in primary and secondary crusher products) has significant potential to reduce grinding energy. Non-economic material can be removed from the comminution process before significant energy costs are incurred through the grinding stages (Pokrajcic, 2010). Whilst a number of ore sorting technologies are available and have been demonstrated at industrially relevant scales for commodities such as diamonds (Riedel and Dehler, 2010), limestone and industrial minerals (Sivamohan and Forssberg, 1991), none have been proven to give the required discrimination for the low grade porphyry copper ores that account for around 60% of future global copper resources (BGS, 2007).

Microwave (MW) energy has been shown to have benefits across a range of mineral processing applications including microwave assisted comminution of ores (Kingman et al., 2004; Jones et al., 2005), enhanced magnetic separation (Kingman and Rowson, 2000), leaching (Al-Harahsheh and Kingman, 2004; Al-Harahsheh, 2005) and exfoliation of vermiculite (Folorunso et al., 2012). MW energy provides selective and volumetric heating; semi-conductive sulphide minerals such as pyrite and chalcopyrite have been shown to heat significantly more than rock forming minerals such as quartz and feldspar (Walkiewicz et al., 1988).

Low power microwave attenuation has been successfully used to sort diamond bearing kimberlite from gabbro in a process developed by De Beers (Sivamohan and Forssberg, 1991; Salter and Nordin, 1993). A 100 mW 10.535 GHz microwave signal was applied to ore fragments; the level of attenuation of the signal was used to either accept or reject each fragment. The technology was successfully scaled to a 100 tonne per hour prototype by replacing the scintillation counter of an M17 radiometric sorting unit with the microwave attenuation system.

The earliest attempt to use microwave heating to discriminate between ore fragments was by Berglund and Forssberg, who

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investigated microwave sorting of a Zinkgruvan sulphide ore (Berglund and Forssberg, 1980). Ore fragments were heated in a multimode microwave cavity and the temperature rise of each fragment measured. No information is available on the sorting criteria, however it was stated that losses of 20% Pb and 25% Zn to the reject fraction were considered too high to warrant further investigation (Sivamohan and Forssberg, 1991).

Microwave heating combined with temperature measurement was studied in further detail by Van Weert and Kondos (2007). The exploratory study on high sulphide and carbonaceous rocks aimed to reject the highly carbonaceous fragments responsible for preg-robbing in cyanide leaching of gold. Test fragments were placed around the edge of the turntable in a 1.1 kW multimode MW cavity operating at 2.45 GHz for 20 s. Fragments were removed from the cavity and the maximum temperature measured using an infra-red (IR) gun, and classified as either hot, medium or cold. Sulphidic and carbonaceous fragments were concentrated in the hot class, however it was not possible to distinguish between sulphidic and carbonaceous fragments based on the maximum temperature measured. Additionally, the orientation of fragments during microwave treatment affected the measured temperature. Although the results were promising in terms of sortability, no attempt was made to quantify the microwave energy input and therefore the economic viability of the process.

A subsequent study by Van Weert et al. (2009) aimed to establish potential conditions for MW-IR sorting of a range of molybdenum and copper sulphide ores. This work established that significant upgrades in valuable mineral content were achievable using the technique. However, the tests were not carried out in a consistent manner, with different treatment times used for each ore; microwave energy inputs were not quantified, making comparison between different samples very difficult. Furthermore, with maximum surface temperatures of over 100 °C, selectively heated mineral phases are likely to have reached much higher temperatures, possibly leading to surface oxidation or even melting of sulphides. As noted in early microwave comminution work by Kingman et al. (2000), such mineral alterations can have negative impacts on downstream flotation processes, due to changes in mineral surface chemistry.

Van Weert et al. (2011) subsequently conducted a study into the microwave heating rates of a range of sulphide minerals. All minerals were crushed to produce two size fractions (approximately 2000 μm and −74 μm). The coarser size fraction was tested as both separated grains and touching (heaped). Higher heating rates were reported when grains were touching, whilst slower microwave heating rates were measured for the finer size fraction. These observations may be due to increased loss of heating to the surroundings due to increased surface area to volume ratio. The conductivity and resulting skin depth of the minerals is also likely to have influenced heating rates, however these were not considered in the investigation.

Recently, MW-IR sorting has been applied to the gradation of iron ores (Ghosh et al., 2013, 2014). 30 fragments of approximately 10 mm were randomly selected from larger samples (mass unknown). Specimens were arranged in a rectangular array on the turntable of a 1.25 kW multimode cavity and heated for 10 s (the time for one revolution). Fragments were then removed from the cavity and imaged using an IR-camera. Tests were repeated 5 times with the same fragment placement and results reported as repeatable, however no attempt was made to place fragments in different positions on the turntable and it was assumed that each fragment received the same cumulative microwave energy dose. In reality this is unlikely, due to the relatively small size of the fragments and the standing wave patterns inherent in domestic multimode microwave cavities.

Following Labview analysis, fragments were classified as either high grade (70% fragment surface at or above 50 °C) or low grade (40% fragment surface below 50 °C). Subsequent chemical assay indicated concentration of iron in the high grade class (67.3%) compared to the low grade class (54.4%). Although the sorting correlation was good, the use of MW-IR sorting for iron ore on a fragment by fragment basis may not be economically viable, due to the relatively high grade of all fragments; again microwave energy input was not quantified.

Recently, a method has been proposed for studying the microwave heating of ores with controlled mineralogies, by using synthetic samples (Rizmanoski and Jokovic, 2015). This is achieved by embedding sulphide mineral grains within a microwave transparent gangue matrix. Previous attempts using a cement or plaster matrix were unsuccessful; larger sulphide grains settled at the bottom of synthetic ore fragments and fragments were too brittle for repeated testing (Van Weert and Kondos, 2008; Rizmanoski and Jokovic, 2015). Rizmanoski developed a fabrication method using polymethyl methacrylate (PMMA) to bind pulverised quartz, creating a hardwearing matrix with dielectric properties similar to those of quartz.

The objective of the paper is to determine the potential for microwave-infrared sorting of ores in multimode cavities with power densities in the order of 1×10^8 W/m^3. Finite difference modelling will be used to determine the microwave heating behaviour of binary ore fragments at a quantified and economically feasible microwave energy input of 0.5 kW h/tonne of ore. Three broad textural aspects will be considered; grain location, grain dissemination and grain size. Synthetic fragments are fabricated using the method developed by Rizmanoski and Jokovic (2015), with textures matching those modelled. Synthetic fragments are treated in a multimode cavity at 2.45 GHz and an equivalent microwave energy dose. Comparison of the modelled and experimental surface temperature rise allows validation of the numerical models. Subsequently, a range of discrete grades representative of fragments in low grade porphyritic ores will be modelled, specifically 0%, 0.10%, 0.25%, 0.35%, 0.55%, 0.65%, 0.85%, 1.00% and 2.00% copper content. The influence of fragment texture and grade on the sorting process will be discussed with respect to potential pilot scale MW-IR ore sorting processes.

2. Materials and methods

Previous experimental work has shown that microwave heating combined with infra-red thermal measurement of fragments' surfaces (MW-IR sorting) can be used to broadly differentiate between high grade and low grade ore fragments based on temperature rise (Van Weert et al., 2009). However, the effect of ore fragment texture, and the response of different textures at different fragment grades commonly seen in porphyry copper ore sorting feed stocks at economically viable microwave energy inputs have not yet been investigated.

In this paper, numerical modelling is used to determine the likely microwave heating response of binary fragments with different textures and grades, to determine the suitability of MW-IR for sorting ore feeds comprising fragments of differing textures. In this work, binary refers to an ore consisting of two minerals only. To validate these models, synthetic fragments of corresponding size, texture and similar microwave heating characteristics are heated in a microwave cavity. The thermal response of these fragments is measured and the results used to validate the representation of binary ore heating and surface thermal profile development. An additional set of binary models are used to determine the range of thermal responses exhibited by fragments of different textures, at grades commonly seen in porphyry copper ores. Finally, the